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Title: Mushy Layer Physics in Sea Ice Models

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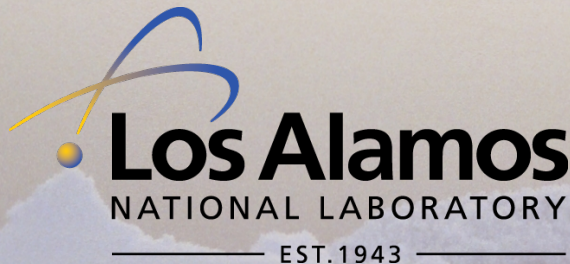
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Mushy Layer Physics in Sea Ice Models

Adrian Turner

Los Alamos National Laboratory

NOAA talk: 19th March 2021



U.S. DEPARTMENT OF
ENERGY

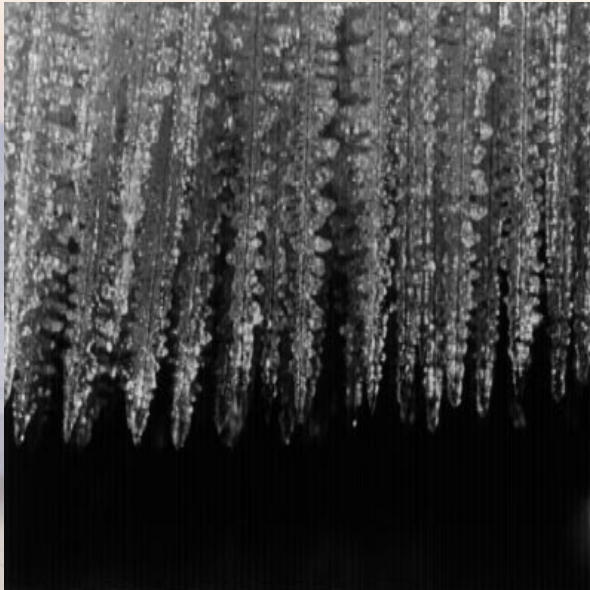
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Overview

- Will talk about prognostic salinity modeling in global climate models
- Developed prognostic salinity ('mushy layer' physics) for CICE in LANL post-doc 2010-2013

Sea ice formation

Worster (1999)



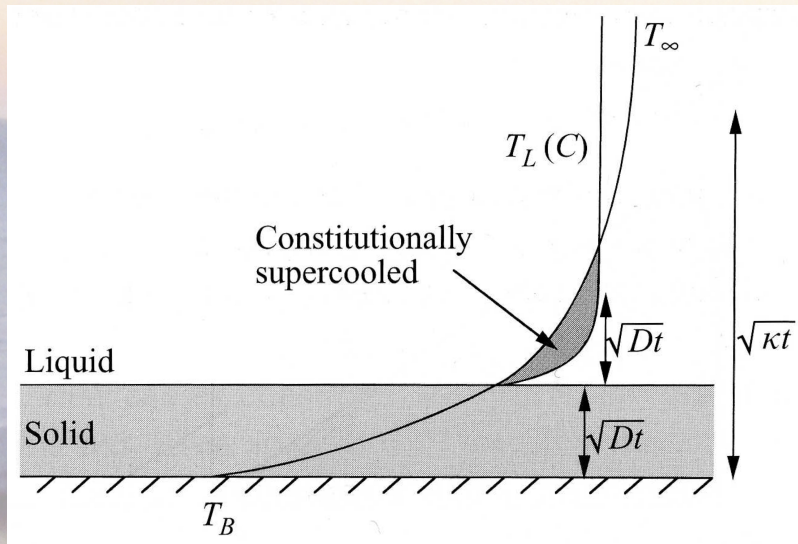
K. M. Golden et al. (2007)



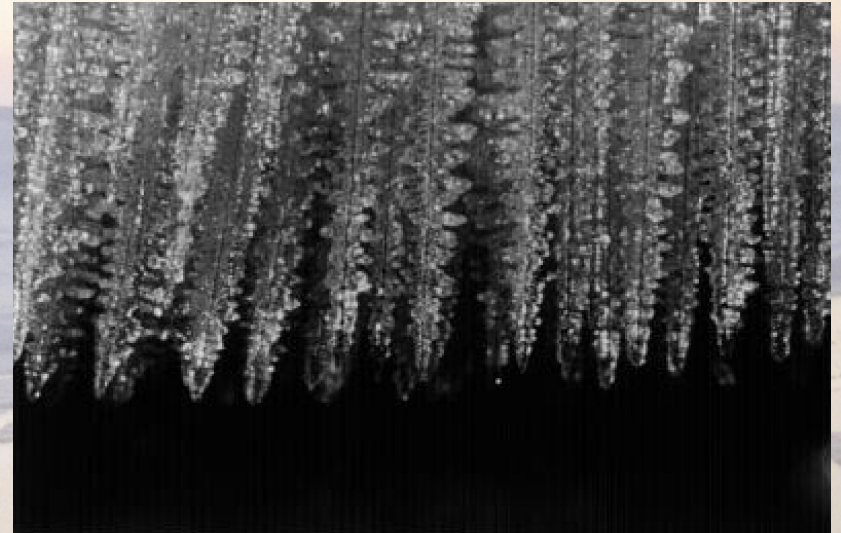
- Freezing interface becomes morphologically unstable during growth
- Brine is trapped between dendritic crystals
- Resulting structure is termed a “mushy layer”
- Pore structure changes dynamically according to changes in temperature and brine pocket salinity
- Brine actively flows through connected brine pockets

Mushy Layer

Mushy layer formation



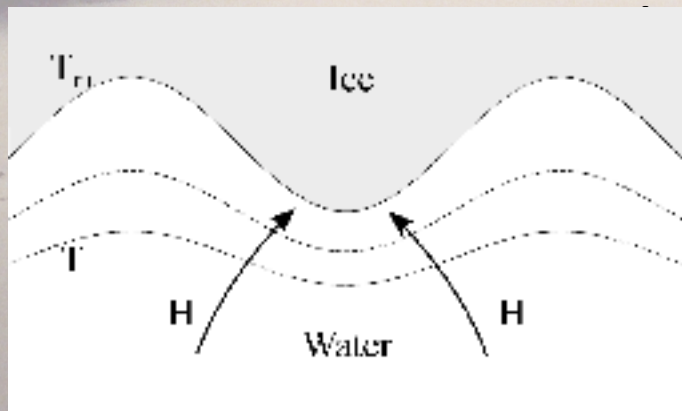
Worster (2000)



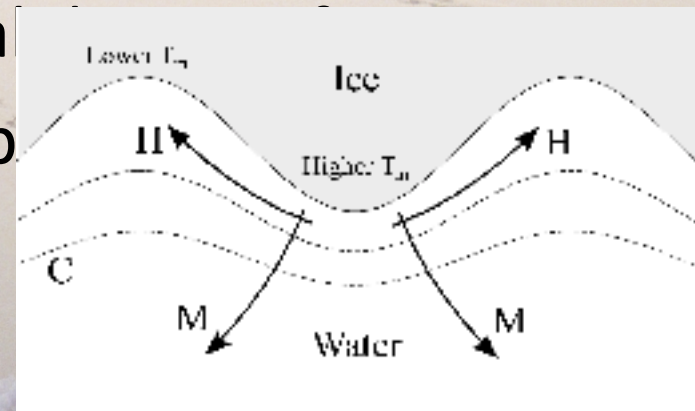
- Growing planar ice rejects all salt ahead of it
- Build up of salt depresses melting temperature ahead of the growing front
- Supercooled region develops – “constitutionally supercooled”

Morphological instability

- Possibility of morphological instability (Mullins & Sekerka 1964)
 - Surface tension stabilizes surface



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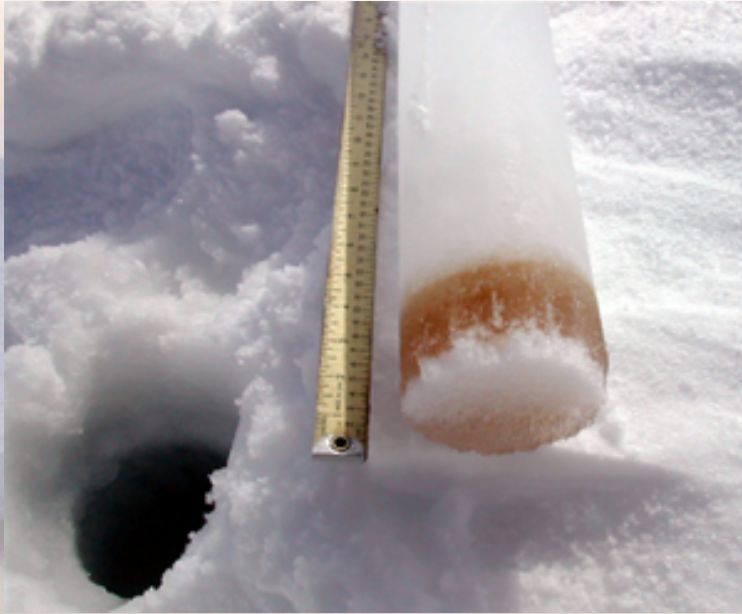


$$\left(\frac{\partial T}{\partial z} \right)_{z=h+} < -\Gamma \left(\frac{\partial C}{\partial z} \right)_{z=h+}$$

Temperature gradient

Solute effects

Effect of salinity structure



NOAA



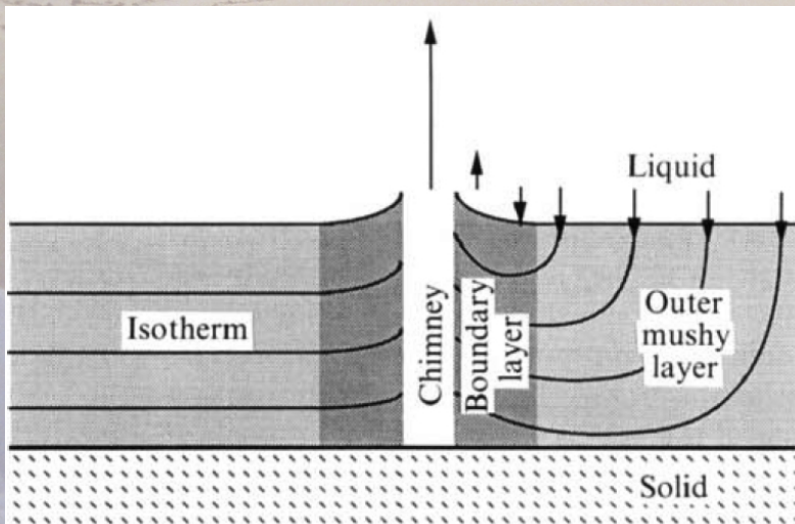
- Sea ice is home to a wide variety of organisms – bacteria, diatoms
- Need to be able to simulate flow of brine around sea ice to model flow of nutrients that supports this life
- Biology affects radiation absorption through albedo
- Salinity profile also effects physical properties – ice strength, melt rate

Lower BC for mushy layer during growth

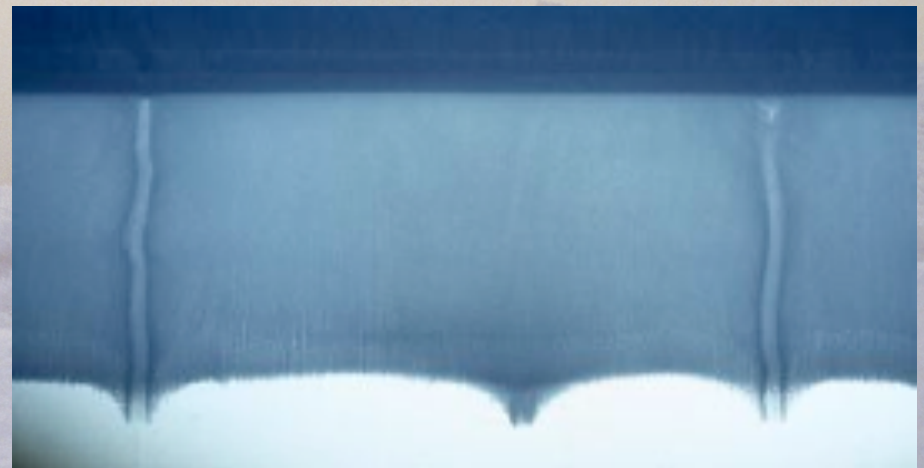
- No clear agreement on what this should be
 - Depends on particular situation
- Popular is the “condition of marginal equilibrium”
 - Mush grows at a speed that just removes constitutional supercooling ahead of the growing interface
$$\left(\frac{\partial T}{\partial z}\right)_{z=h^-} = \left(\frac{\partial T}{\partial z}\right)_{z=h^+}$$
 - This often leads to $\Phi=0$ at the interface, as is usually the case with sea ice
- Some people just use $\Phi=0$ at the interface
- $\Phi=0$ at the interface is annoying – can’t directly use Stefan condition
$$\rho L \phi \frac{dh}{dt} = k_i \left. \frac{\partial T}{\partial z} \right|_{z=h^-} - k_l \left. \frac{\partial T}{\partial z} \right|_{z=h^+}$$

Convection and Gravity Drainage

- Growing ice has high salinity brine overlaying low salinity brine – higher density brine over lower density brine
- Convection overturning of brine in ice matrix
- Brine motion results in change in ice matrix structure – development of chimneys
- Resulting brine loss from ice responsible for desalination of ice

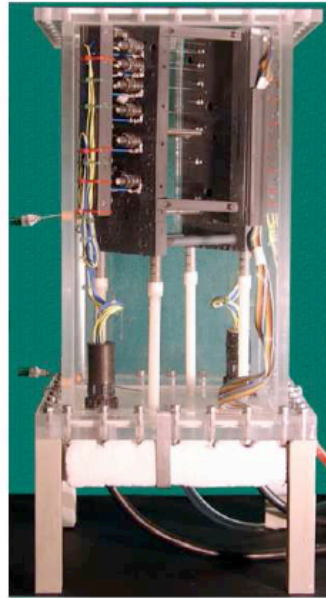
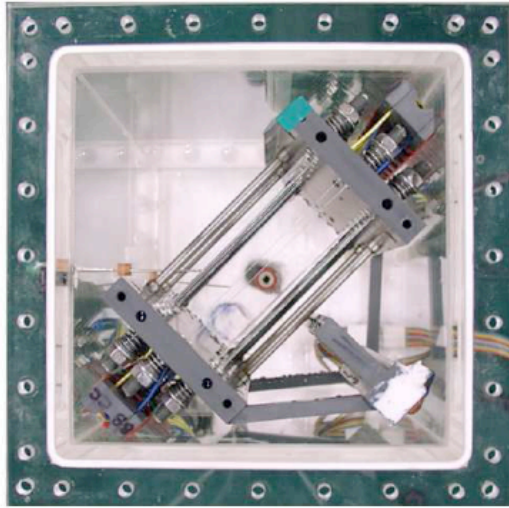


Worster (1991)



Worster (2000)

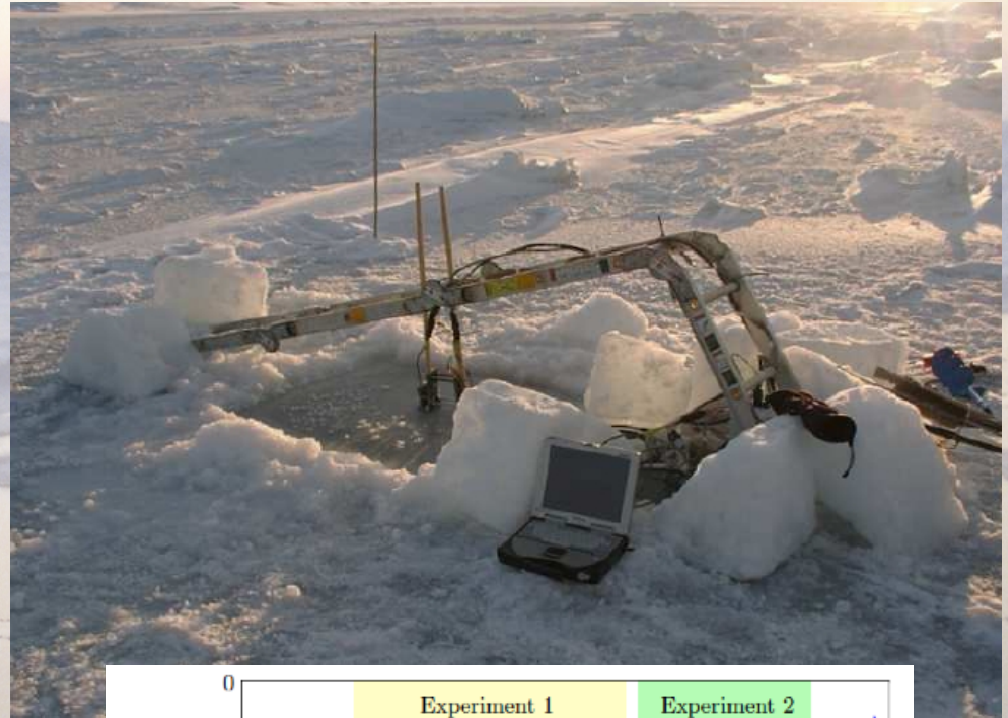
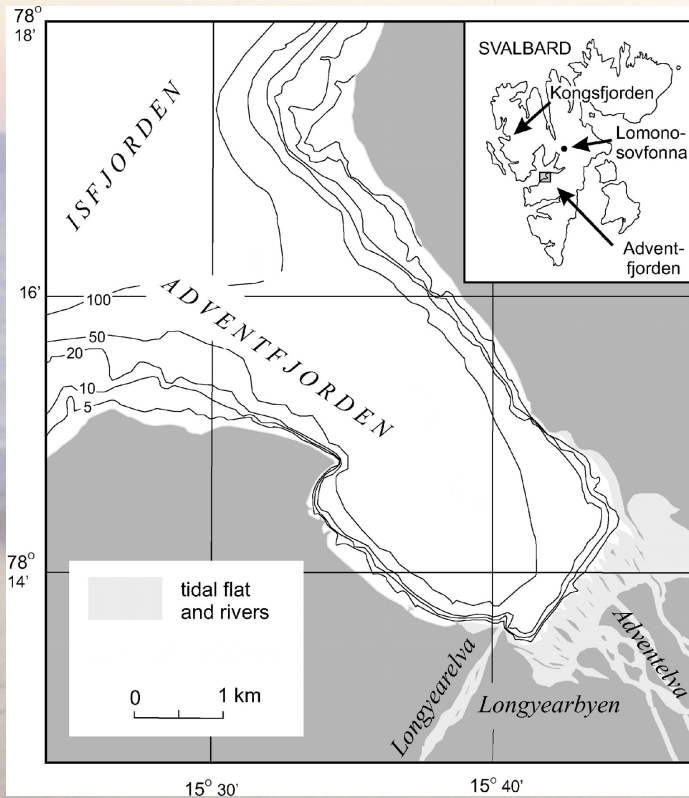
Experimental Results of Convection



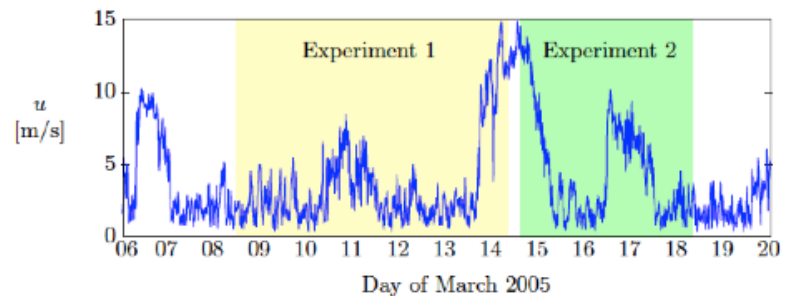
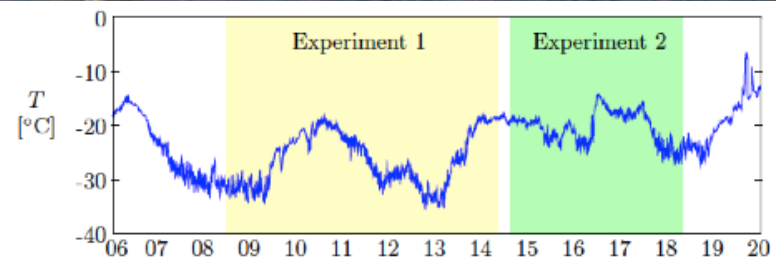
Notz (2005)

- Desalination experiments of Dirk Notz (2005) measured bulk salinity, temperature and solid fraction during ice growth
- 40×20×20cm Perspex tank with custom instrumentation
- Impedance measured between Platinum wires, temperature by thermistors.
- Solid fraction determined from wires. Bulk salinity inferred from temperature and solid fraction using Liquidus curve.

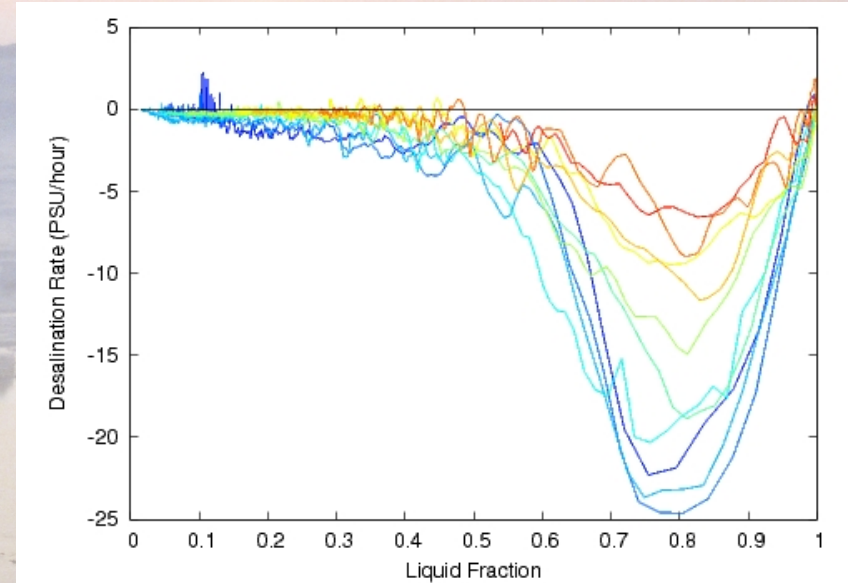
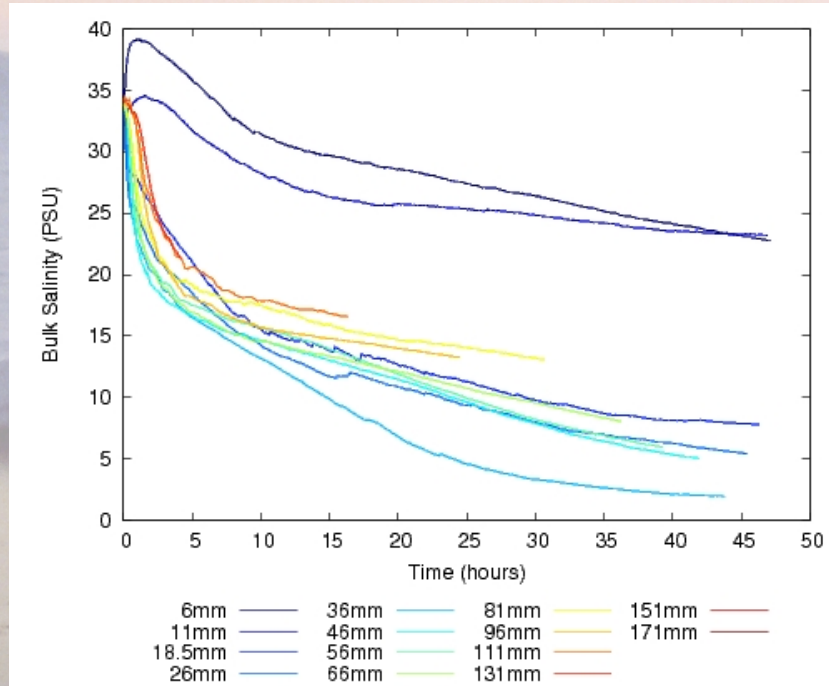
Fieldwork (Notz 2008)



- Two sets of fieldwork experiments in Adventfjorden, Svalbard
- Ice grown from hole cut in ice

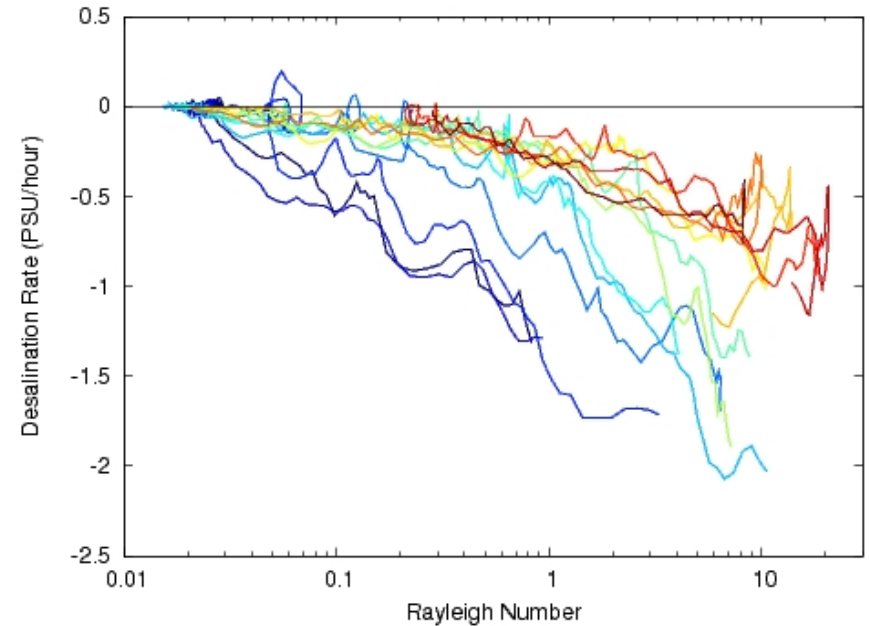
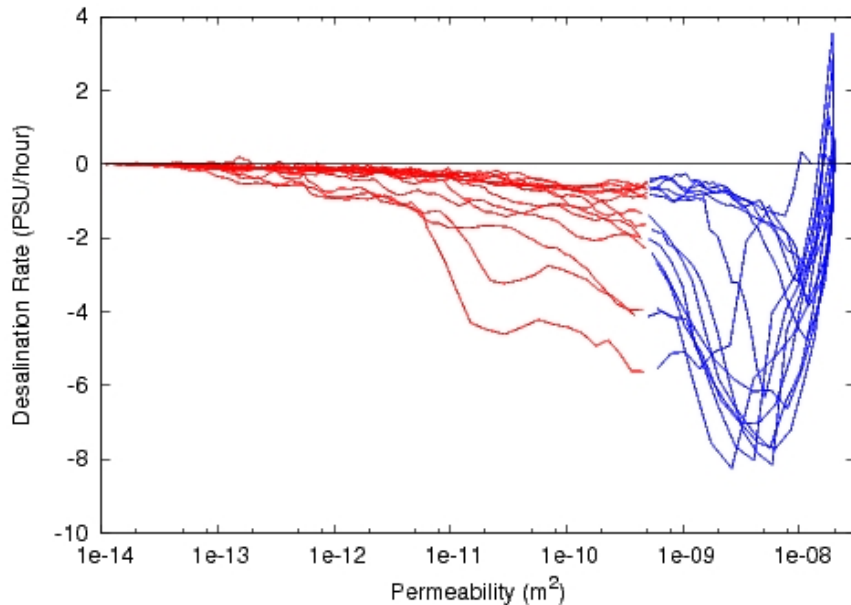


Experimental observation of drainage



- Gravity drainage shows two distinct phases
 - An initial rapid drainage to ~20 PSU that lasts a few hours
 - A slow drainage that is ongoing at ~0.25 PSU/hour

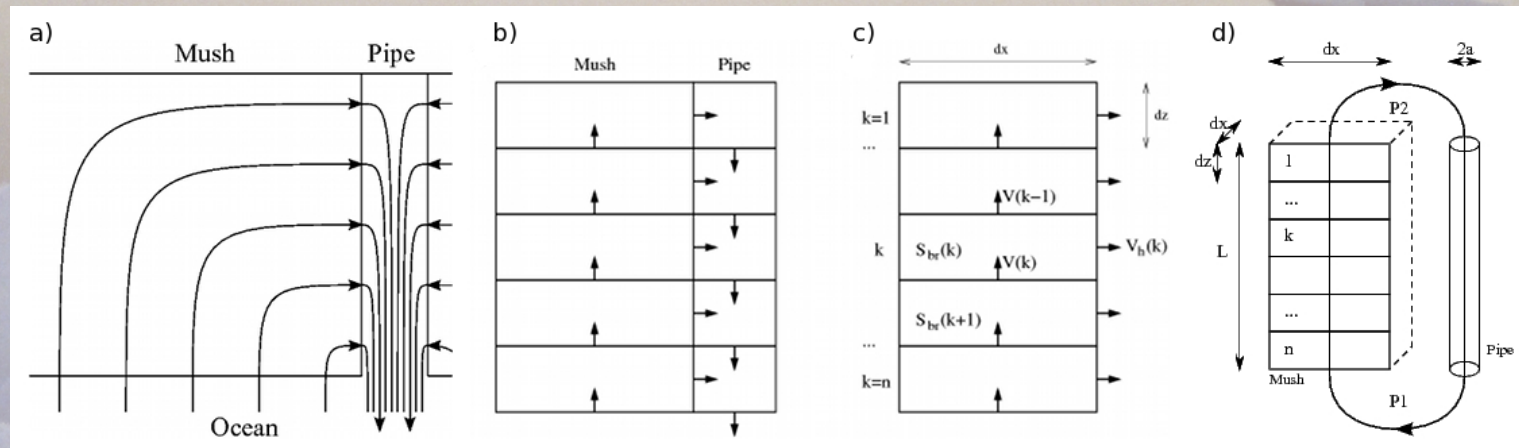
Fieldwork observation of drainage



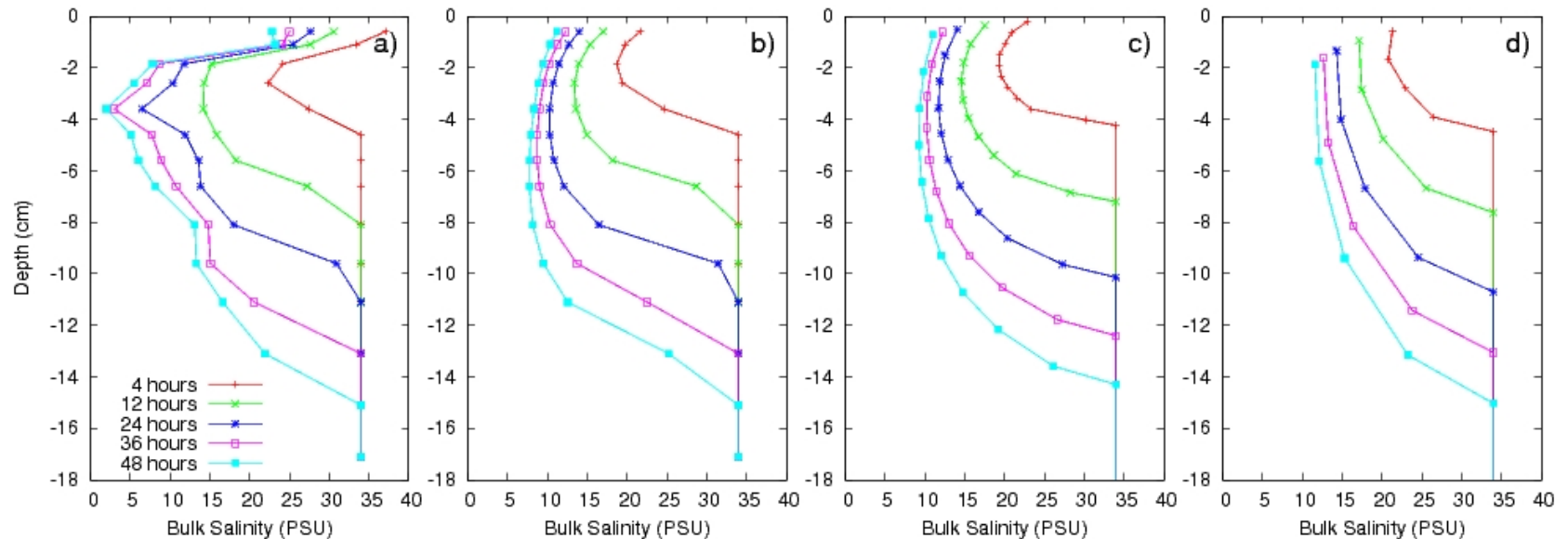
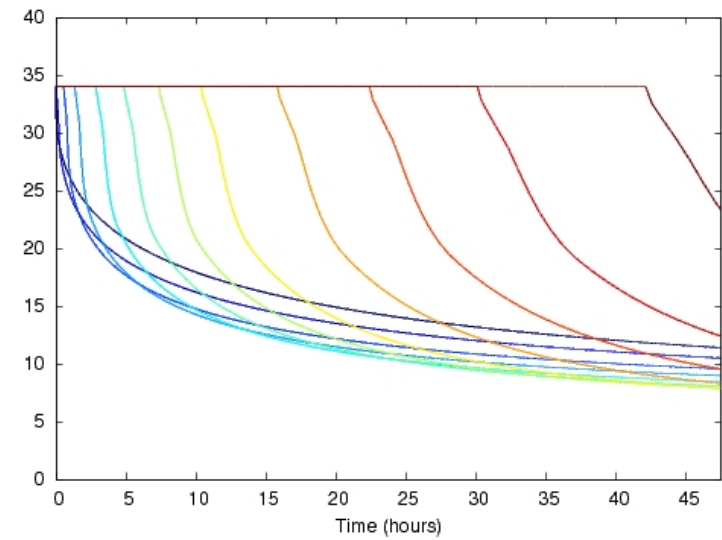
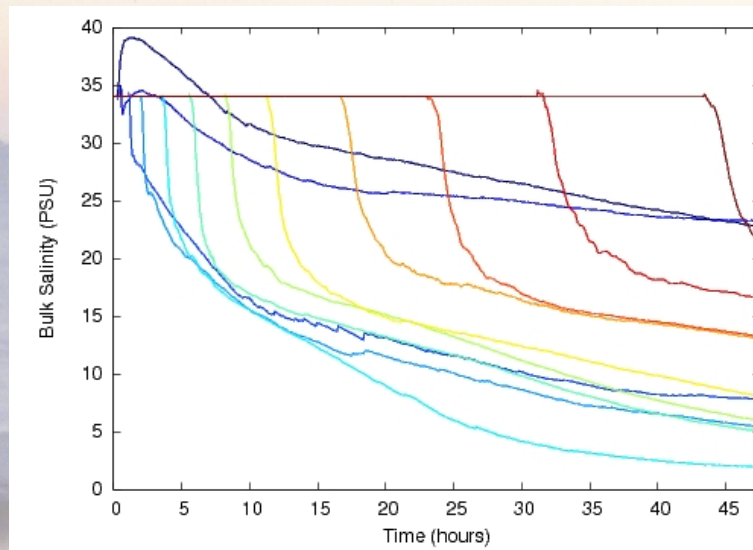
- Divide first fieldwork period data into initial and later drainage phase by permeability
- Examine desalination rate for later drainage versus mush Rayleigh number
- No evidence of cutoff in desalination with drainage rate
- No critical Rayleigh number

Drainage parameterizations

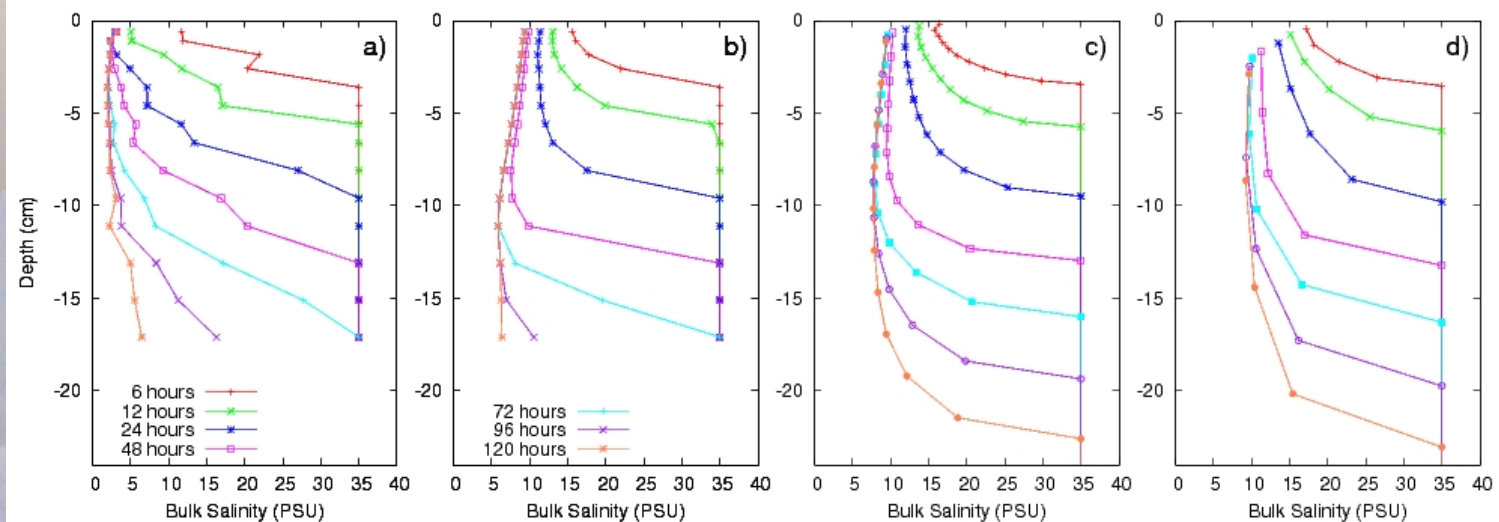
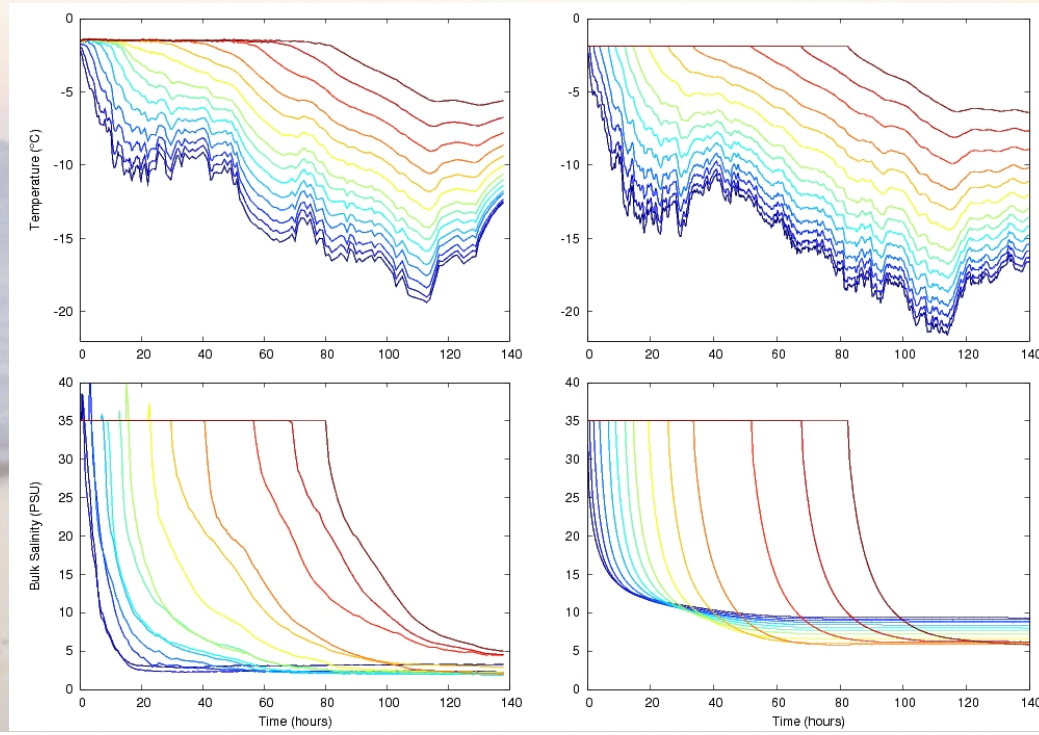
- Have two parameterizations – one for each phase
- Model initial rapid phase with explicit flow calculation assuming upflow in mush and downflow in narrow pipe
- Modify by critical Rayleigh number
- Use flow rate to advect brine upwards through the mush, resulting in desalination
- Model later desalination with source term proportional to porosity and brine density difference with the ocean



Results - experiment



Results - fieldwork



Icepack vertical thermodynamics

- Solve mushy layer equations
 - Brine salinity given by liquidus relation
 - Enthalpy and liquid fraction:

$$\begin{aligned} q &= \phi q_{br} + (1 - \phi) q_i \\ &= \phi \rho_w c_w T + (1 - \phi) (\rho_i c_i T - \rho_i L_0) \end{aligned}$$

$$\phi = \frac{S}{S_{br}}$$

- Enthalpy and Salinity prognostic equations:

$$\frac{\partial q}{\partial t} = \frac{\partial}{\partial z} \left(K \frac{\partial T}{\partial z} \right) + w \frac{\partial q_{br}}{\partial z} + F$$

$$\frac{\partial S}{\partial t} = w \frac{\partial S_{br}}{\partial z} + G$$

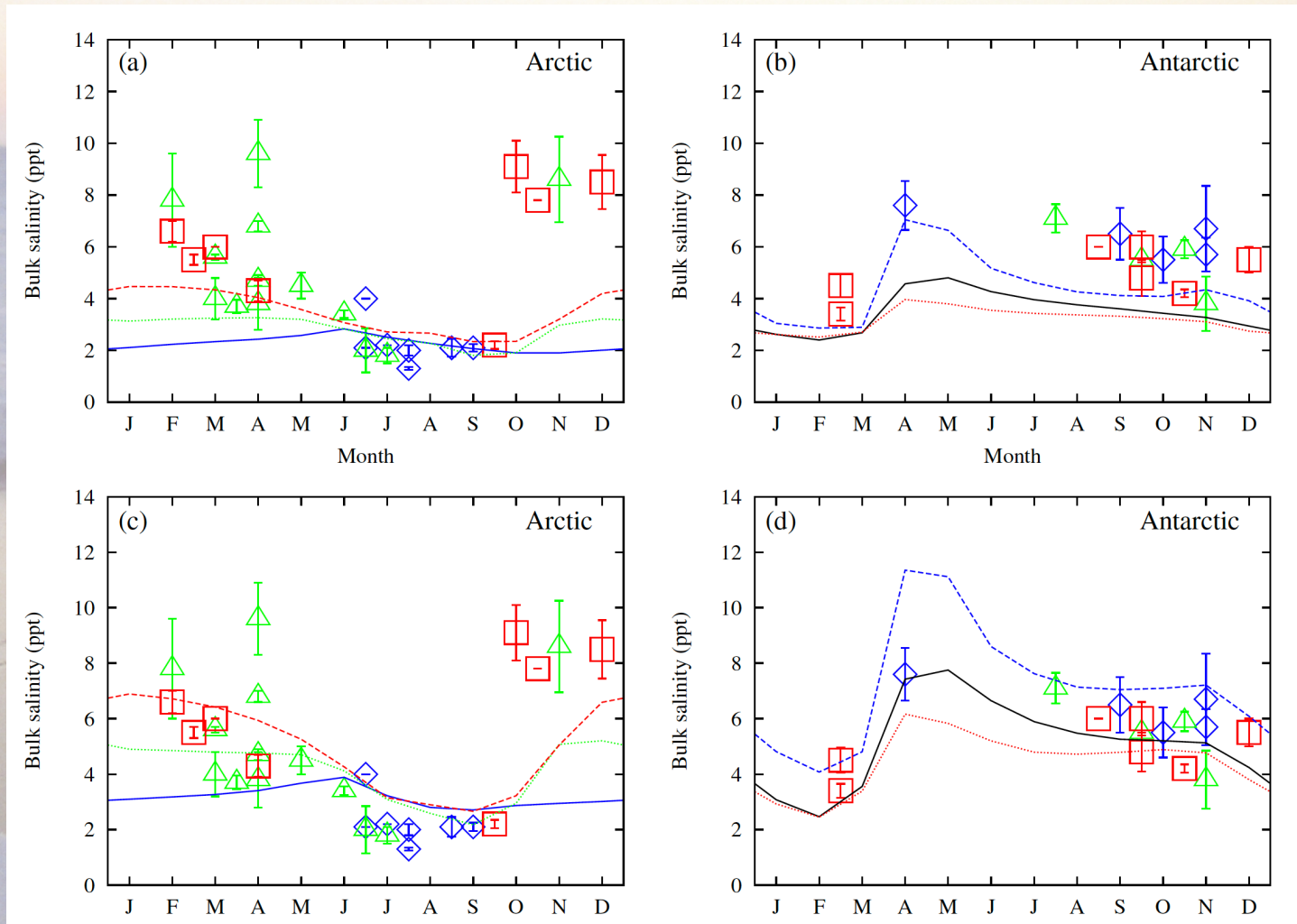
- w advection speed from gravity drainage and flushing
- Slow salinity relaxation

$$\left. \frac{\partial S(z)}{\partial t} \right|_{slow} = -\lambda (S(z) - S_c).$$

- Basil ice growth ($\phi_0 = 0.85$)

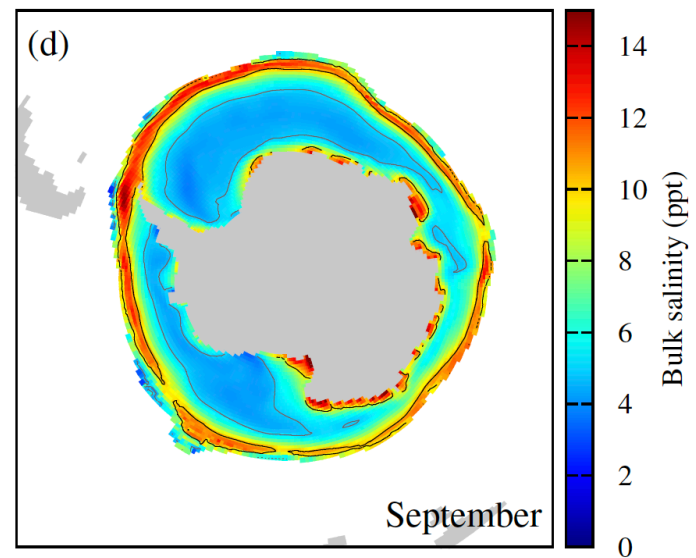
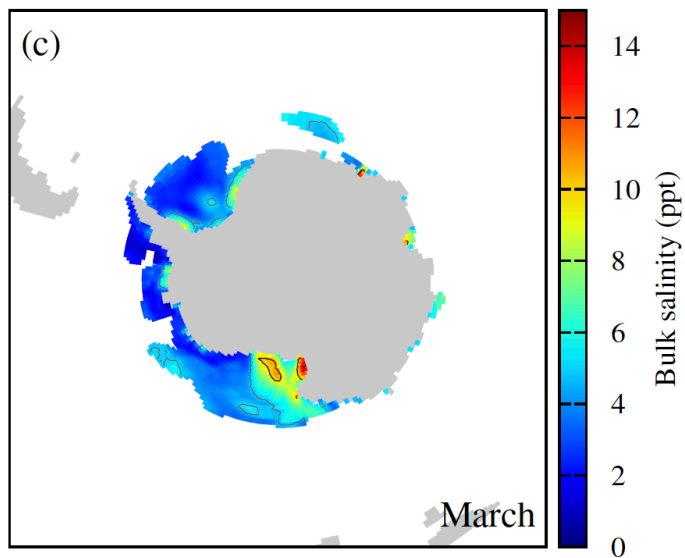
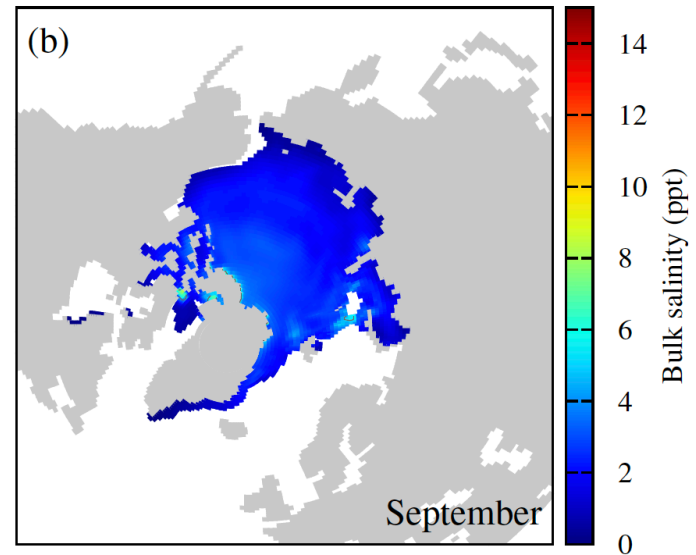
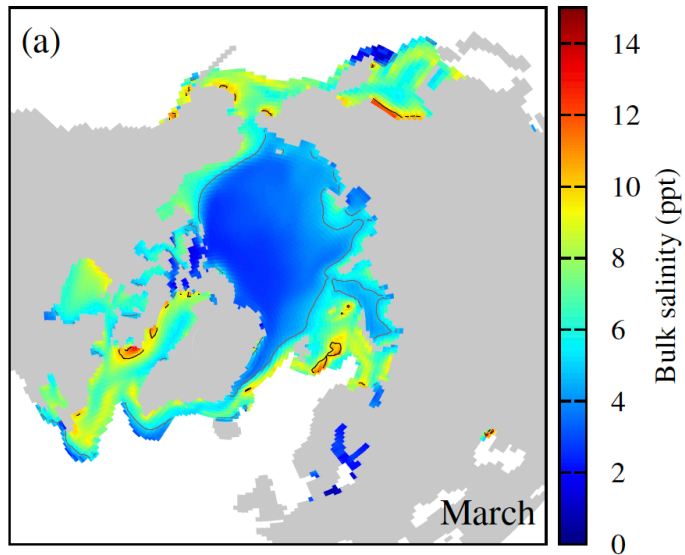
$$(1 - \phi_0) L_0 \Delta h = (F_{cb} - F_{bot}) \Delta t$$

Global Sims I



For Arctic model results regions are: (solid blue) Arctic Ocean, (green dots) peripheral seas, (red dashes) outer Arctic. For Arctic observations regions are: (blue diamonds) Arctic Ocean and Fram Strait, (green triangles) peripheral seas, (red squares) outer Arctic. For Antarctic model results regions are: (solid black) global Southern Ocean, (blue dashes) West Pacific sector, (red dots) Weddell Sea. For Antarctic observations regions are: (blue diamonds) West Pacific and Indian sectors, (red squares) Weddell Sea, (green triangles) Ross, Amundsen and Bellingshausen seas.

Global Sims II



Two modes of sea-ice gravity drainage: A parameterization for large-scale modeling

Adrian K. Turner,¹ Elizabeth C. Hunke,¹ and Cecilia M. Bitz²

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 **AGU** PUBLICATIONS



Journal of Geophysical Research: Oceans

RESEARCH ARTICLE

10.1002/2014JC010358

Key Points:

- Sea-ice salinity is simulated in the CICE global sea-ice model
- Gravity drainage, melt pond flushing and snow-ice formation determine

Impacts of a mushy-layer thermodynamic approach in global sea-ice simulations using the CICE sea-ice model

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JAMES

Journal of Advances in
Modeling Earth Systems

RESEARCH ARTICLE

10.1029/2020MS002154

Special Section:

Community Earth System
Model Version 2 (CESM2)
Special Collection

Impact of a New Sea Ice Thermodynamic Formulation in the CESM2 Sea Ice Component

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